

Technical Paper

Investigation of the variable elastic unloading modulus coupled with nonlinear kinematic hardening in springback measuring of advanced high-strength steel in U-shaped process



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ABSTRACT

Advanced high strength steels are widely used in the automotive industry due to their appropriate strength to weight ratio. This alloy has unique hardening behavior and variable unloading elastic modulus. In this paper, an analytical model is introduced to predict springback in U-shaped bending process of normal and pre-strained DP780 dual phase steel stripes. It is based on the Hill48 yield criterion and plane strain condition. In this model, the effect of forming history, sheet thinning and the motion of the neutral surface on the springback is taken into account. The anisotropic nonlinear kinematic hardening model (ANK) is used to consider the impact of complex deformation including stretching, bending and reverse bending. This model is able to investigate the Bauschinger effect, transient behavior and permanent softening. Also, a nonlinear function of plastic strain is implemented to capture the variable unloading elastic modulus. This model is used for the Numisheet2011 benchmark U-shaped bending problem. The effect of the sheet holder force, the coefficient of friction, thickness, material anisotropy, hardening parameters, pre-strain and variable elastic modulus on the sheet springback is studied. It can be seen that analytical model with constant young's modulus has better accuracy in predicting springback angles than FEM solutions. Also in the case of variable young's modulus, FEM solution has better agreement with experiments in comparison with the analytical model.

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1. Introduction

Springback is an undesired phenomenon during forming process of metallic parts, which must be modified in the optimization process. Materials with higher strength and lower modulus of elasticity have greater springback. For example, advanced high-strength steels (AHSS) have more springback compared to conventional steels. Thus, multi-step forming processes are usually used in forming these alloys. Therefore, investigating the effect of pre-strain on the consequent forming processes of this material is very important [1,2]. U-shaped bending processes are used in the production of components such as channels, beams, and frames. In this process, sheet metals experience complex deformation, including stretch-bending, stretch-unbending operation and reverse bending. Therefore, after unloading in addition to the springback, the curvature of the sidewalls will be seen. Accurate springback prediction in this forming process needs hard-

ening models which can consider complex behaviors of material in reverse loading stage. Various methods, including analytically [3–6], semi-analytical methods [7,8] and finite element method (FEM) [9,10] are used to predict springback of bending process. Analytical models can be used only for simple part geometries. FEM is time-consuming in comparison with the analytical methods and is sensitive to numerical parameters such as the type and size of the elements, integration scheme, yield criteria and strain hardening rule.

Springback prediction accuracy increases when mechanical behavior is well described so the amount of springback depends on two main factors, namely; the stresses in the material before unloading and unloading modulus [5,11,12]. The elastic modulus of material during the unloading process is not constant and it is a function of plastic strain. The mechanical behavior of materials in reverse loading due to reverse strain in the sheet metal forming process is highly regarded [12–14]. Fig. 4 shows the flow stress curve on the outer surface of the sheet while bending around die arc. Four features can be seen in this curve that include: Bauschinger effect (material yielding during reverse loading in less stress) [15,16], transient behavior (fast hardening in elastic-plastic transition zone

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Nomenclature

r	Curvature radius of the bending surface
R_m	Curvature radius of the sheet middle surface
R_n	Curvature radius of the sheet neutral surface
R_o	Curvature radius of the sheet convex surface
R_i	Curvature radius of the sheet concave surface
t_0	Sheet initial thickness
t	Sheet thickness after bending process
$\bar{r}$	Transverse anisotropy coefficient
G	Transverse anisotropy coefficient in plane strain condition
F_{lim}	Sheet limiting force
P_{hmax}	Maximum blank holding force
I	Cross-section moment of inertia per unit width
L	Length of the lateral surface
C_t	Half of the tensile elastic region
C_c	Half of the compressive elastic region
R_{yt}	Curvature radius which yield occurs during reverse tensile loading
R_{yc}	Curvature radius which yield occurs during reverse compressive loading

Greek symbols

σ_0	Initial yield stress
α_{fowt}	Backstress during the forward tensile loading
α_{fowc}	Backstress during the forward compressive loading
α_{revt}	Backstress during the reverse tensile loading
α_{revc}	Backstress during the reverse compressive loading
$\bar{\epsilon}_{fow}^p$	Effective plastic strain during the forward loading
$\bar{\epsilon}_{rev}^p$	Effective plastic strain during the reverse loading
$\bar{\sigma}_{fowt}$	Effective plastic stress during the forward tensile loading
$\bar{\sigma}_{fowc}$	Effective plastic stress during the forward compressive loading
$\bar{\sigma}_{revt}$	Effective plastic stress during the reverse tensile loading
$\bar{\sigma}_{revc}$	Effective plastic stress during the reverse compressive loading
$\bar{\epsilon}_{fowy}$	Effective plastic strain which yield occurs during forward loading
$\bar{\epsilon}_{revy}$	Effective plastic strain which yield occurs during reverse loading
$\bar{\epsilon}_*^p$	The amount of the blank pre-strain
φ	Angle of the each sheet cross-section
θ	Total curvature angle of the punch and die corner
μ_d	Die friction coefficient
μ_p	Punch friction coefficient
$\sigma_{\theta fow}$	Tangential stress during the uniaxial forward loading
ν	Poisson's ratio
$\sigma_{m\theta}$	Tangential stress in the sheet middle surface
ρ_{sw}	Sidewall curvature radius
$\epsilon_{\theta rev}$	Tangential strain during the reverse loading
$\bar{\epsilon}_{rev}$	Total effective strain during the reverse loading
$\epsilon_{\theta u}$	Tangential strain after the unloading process
$\sigma_{\theta rev}^e$	Tangential elastic stress during the reverse loading
$\Delta\theta_{sw}$	Springback angle of the region III
$\Delta\theta_1$	Springback angle of the region II
$\Delta\theta_2$	Springback angle of the region IV

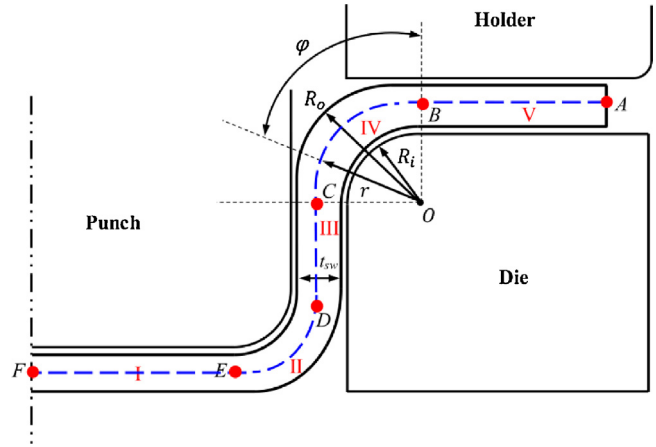


Fig. 1. The schematic of the sheet U-bending part and different regions.

[17], work hardening stagnation (stopping or slow the rate of work hardening) [18].

The main objective of this paper is a quantitative analysis of the material structural behavior, geometrical and forming parameters, pre-strain effects and variable elastic modulus as the main factors that influence on the springback prediction. For this purpose, an analytical model is presented based on a combined isotropic-kinematic hardening (ANK) model [19], Hill48 quadratic yield function and plane strain condition. Also, unloading modulus is expressed as a function of plastic strain. This model is used for predicting springback at normal and pre-strained DP780 stripes based on the conditions provided from the Numisheet2011 Benchmark.

2. Analysis of sheet U-shaped stretch-bending process

Deformation in U-shaped bending process divided into five regions as shown in Fig. 1. Regions I and V are straight and are in contact with straight edges of punch and die. Although in reality, these regions should be curved, but to simplicity, they are assumed straight due to the neglecting bending moment applied to the two parts. Regions II and IV are under tension-bending around the corners of punch and die. Region III is free and experiences the complex deformation history. At first, the region IV is bent around the die corner and then be straight converted to the sidewall. Due to the bending moment applied to Region III, this region should have a curvature, but considering that the space between the die and punch is small compared to the punch stroke this region during the forming process straight assumed. However, after unloading the sheets in this Region due to spring-back has rather a large curvature.

Deformation of the sheets at the edges of the punch and die can be considered as a stretch-bending process as shown in Fig. 2 with considering the following assumptions:

1. According to the Kirchhoff-Love plate theory, straight lines normal to the neutral surface remain straight during the stretch-bending process.
2. Sheet width in comparison with its thickness is large enough so the strain in the width direction ϵ_z is zero.
3. Transverse stress (σ_r) is neglected.
4. Volume conservation law during the stretch-bending process is considered.
5. During the sheet reverse stretch-bending process, the thickness of sheet assumed to be unchanged.
6. The young's modulus is a function of plastic strain

against the forward loading), permanent softening (existing a distance between the flow curves in forward and reverse loading)

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